

Higher media multi-tasking activity is associated with smaller gray-matter density in the anterior cingulate cortex

Article (Published Version)

Loh, Kep Kee and Kanai, Ryota (2014) Higher media multi-tasking activity is associated with smaller gray-matter density in the anterior cingulate cortex. PLoS ONE, 9 (9). e106698. ISSN 1932-6203

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/id/eprint/50361/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.



Higher Media Multi-Tasking Activity Is Associated with Smaller Gray-Matter Density in the Anterior Cingulate Cortex

Kep Kee Loh^{1,3*}, Ryota Kanai^{2,3}

1 Cognitive Neuroscience Laboratory, Duke-NUS Graduate Medical School, Singapore, Singapore, **2** Sackler Centre for Consciousness Science, University of Sussex, Brighton, United Kingdom, **3** Institute of Cognitive Neuroscience, University College London, London, United Kingdom

Abstract

Media multitasking, or the concurrent consumption of multiple media forms, is increasingly prevalent in today's society and has been associated with negative psychosocial and cognitive impacts. Individuals who engage in heavier media-multitasking are found to perform worse on cognitive control tasks and exhibit more socio-emotional difficulties. However, the neural processes associated with media multi-tasking remain unexplored. The present study investigated relationships between media multitasking activity and brain structure. Research has demonstrated that brain structure can be altered upon prolonged exposure to novel environments and experience. Thus, we expected differential engagements in media multitasking to correlate with brain structure variability. This was confirmed via Voxel-Based Morphometry (VBM) analyses: Individuals with higher Media Multitasking Index (MMI) scores had smaller gray matter density in the anterior cingulate cortex (ACC). Functional connectivity between this ACC region and the precuneus was negatively associated with MMI. Our findings suggest a possible structural correlate for the observed decreased cognitive control performance and socio-emotional regulation in heavy media-multitaskers. While the cross-sectional nature of our study does not allow us to specify the direction of causality, our results brought to light novel associations between individual media multitasking behaviors and ACC structure differences.

Citation: Loh KK, Kanai R (2014) Higher Media Multi-Tasking Activity Is Associated with Smaller Gray-Matter Density in the Anterior Cingulate Cortex. PLoS ONE 9(9): e106698. doi:10.1371/journal.pone.0106698

Editor: Katsumi Watanabe, University of Tokyo, Japan

Received: February 25, 2014; **Accepted:** August 8, 2014; **Published:** September 24, 2014

Copyright: © 2014 Loh, Kanai. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: Funding for this project came from a PRESTO grant from the Japan Science and Technology Agency. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* Email: lohkeepke@gmail.com

Introduction

Media multitasking, or the concurrent consumption of multiple media forms, is increasingly prevalent in modern society [1] and has been associated with decreased cognitive control abilities [2] as well as negative psychosocial impacts such as depression and social anxiety [3], negative social well-being [4], and poor academic performance [5]. However, at this juncture, little is known about the neural processes associated with media multi-tasking. The present study investigated relationships between media multitasking activity and brain structure variability. Research has demonstrated that brain structure can be altered with prolonged exposure to novel environments [6] as well as training and experience [7,8]. Furthermore, regional variability in grey and white matter, assessed via Voxel-Based Morphometry (VBM) reliably predicts individual differences in a range of cognitive functions (see [9] for a review). Based on the above findings, we hypothesized that differential engagements in media multitasking would likewise reflect differences in regional brain structures.

In the current investigation, the Media-Multitasking Index (MMI, [2]) is adopted as a measure of trait media-multitasking. MMI scores have been consistently associated with individual performance on cognitive control tasks [2,10,11]. As such, they serve as a reliable behavioral correlate with brain structure variability. We expected that an individual's MMI score would

reflect brain structure differences, specifically in cognitive control and multitasking regions. Past research has converged on the role of prefrontal cortical regions in cognitive control [12,13,14,15]. Based on a lesion study by [16], distinct regions are involved in dissociable aspects of multitasking: the anterior and posterior cingulates are involved in retrospective memory, and the prefrontal regions are implicated in prospective memory and planning. As such, we expected to find associations between media multitasking activity and the structural variability in these regions. Media multitasking activity is closely linked with personality traits (i.e. neuroticism and extraversion [3]), which in turn, are predictive of structural differences in the brain [17]. As such, the association between media multitasking and brain structure might be confounded by these trait differences. To investigate this possibility, relationships between MMI and Big Five personality traits are also examined.

We obtained MMI scores, Big Five personality trait measures and magnetic resonance imaging (MRI) scans in 75 healthy adults that were relatively well-acquainted with computers and media technologies. To examine the relationship between media multitasking activity and brain structure variability, we first correlated individual MMI scores with regional gray matter density at a whole-brain level via optimized VBM [18]. We also examined correlations between the Big Five traits and MMI

scores. To shed light on the functional significance of our obtained structural differences, we analyzed resting state brain activity to elucidate associations between MMI scores and functional connectivity within the brain.

Methods

Participants

75 healthy adults (mean age = 24.6, SD = 5.0, 38 males) recruited from the University College London (UCL) psychology participant pool took part in the current study after providing informed written consent. The study was approved by the local UCL ethics committee (ethics application code: 2213/002). We screened participants to include university students and staff that were well-acquainted with computers and media technologies. They were reimbursed in cash for their participation. Among the 75 participants who took part in the VBM study, fMRI data were collected from a subset of 40 participants. Gender, age, education level and MMI scores did not differ significantly between the two samples (Table 1).

Modified Media Multitasking Questionnaire

A modified version of the Media Multi-tasking Questionnaire [2] was administered to all participants. The MMI provided a stable measure of an individual's trait media multi-tasking activity. The questionnaire consisted of two main sections: The first section listed 12 common media types and participants reported the total number of hours per week they spent using each medium. In the modified version used in the present study, 10 media types were retained from [2]: Print media, television, computer-based video, music, voice calls using mobile or telephone, instant messaging, Short Messaging Service (SMS) messaging, Email, web surfing and other computer-based applications. The item "video or computer games" was modified to include games on mobile phones. The item "non-music audio" was replaced with "using social networking sites". The changes were made to better reflect current trends in media consumption. The second section consisted of a matrix that involved participants indicating how much they concurrently used all the other types of medium as they used a primary medium. Amount of concurrent use was indicated on a scale of 1 to 4 (1 = "Never", 2 = "A little of the time", 3 = "Some of the time" and 4 = "Most of the time"). The participants' responses were first recoded as follows: "Never" = 0, "A little of the time" = 0.33, "Some of the time" = 0.67 and "Most of the time" = 1. Summation of the recoded responses for each primary medium

yielded the mean number of media concurrently used when using a primary medium. The MMI was calculated based on the following formula:

$$MMI = \sum_{i=1}^{11} \frac{m_i \times h_i}{h_{total}}$$

Where m_i is the mean number of media concurrently used while using primary medium, i ; h_i is the number of hours per week spent using the primary medium, i ; and h_{total} is the total number of hours per week spent using all media forms.

Big Five Inventory

The Big Five Inventory (BFI; [19]) provided a brief and reliable 44-item measure for the Big Five personality factors: extraversion (8 items), agreeableness (9 items), conscientiousness (9 items), neuroticism (8 items) and openness to experience (10 items). We adopted the BFI to examine associations between MMI and Big Five personality traits in our sample.

MRI Data Acquisition

A 1.5 T Siemens Avanto scanner (Siemens Medical, Erlangen, Germany) was used to acquire high-resolution T1-weighted structural images for each participant (MPRAGE; 1 mm³ cubic voxels; 160 slices; TR = 2730 ms; TE = 3.57 ms). Functional MRI data were acquired using ascending T2*-weighted gradient-echo echo-planar imaging (EPI) sequences sensitive to BOLD contrast. Each acquisition consisted of 32 oblique slices, 3.0×3.0 mm resolution, 2.0 mm in thickness with 1.0 mm slice gap. The EPI slices were angled individually for each subject to reduce susceptibility artifacts from the nasal cavity and to maximize coverage for the orbitofrontal regions and posterior parietal cortex, while sacrificing the coverage over the temporal pole. As such the final orientation ranged between 8° to 16°. The time interval between two successive acquisitions of the same slice was 2528 ms with a flip angle of 90 degrees and a 44 ms echo time. The field of view was 192×192 mm. The digital in-plane resolution was 64×64 pixels with a pixel dimension of 3.0×3.0 mm. All data were acquired with a 32-channel head coil. During the functional MRI scan, participants were instructed to simply keep still, keep eyes open, and not think about anything in particular. One run consisted of 180 volume acquisitions and the initial 6 volumes were discarded from the analysis to avoid

Table 1. Comparisons between demographic characteristics and MMI scores of participants involved in VBM analyses and functional connectivity analyses.

Variable	VBM	Functional Connectivity	Statistic
n	75	40	
Gender (male)	38	21	$\chi^2 = 0.04$, $df = 1$, $p = 0.85$.
Age (years)	24.56 (5.00) ^a	24.45 (5.03) ^a	$t = 0.11$, $df = 113$, $p = 0.91$.
Highest Attained Education			$\chi^2 = 0.54$, $df = 2$, $p = 0.76$.
PhD, Masters Degree	26	16	
Bachelors Degree	32	17	
High School	17	7	
MMI Score	3.66 (1.58) ^a	3.61 (1.72) ^a	$t = 0.16$, $df = 113$, $p = 0.88$.

^aMean (standard deviation) for age and MMI scores.

doi:10.1371/journal.pone.0106698.t001

confound of unsteady magnetization. The resting state fMRI run took approximately 7.5 minutes.

Voxel-Based Morphometry (VBM) Analysis

Voxel-based morphometry (VBM; [20]) is a commonly used neuroimaging analysis technique that enables voxel-wise statistical analyses of pre-processed MRI images. The high-resolution T1-weighted structural scans were analyzed with VBM via Statistical Parametric Mapping (SPM8, Wellcome Department of Cognitive Neurology). The images were first segmented for grey and white matter. Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra (DARTEL) was subsequently performed to co-register the grey matter images. To ensure that regional grey matter volume was maintained after the registration, registered images were modulated by the Jacobian determinant of the flow fields computed by DARTEL. The registered grey matter images were smoothed with a Gaussian kernel (full width at half maximum = 10 mm) and were then transformed and normalized to Montreal Neurological Institute (MNI) stereotactic space for further multiple regression analysis.

Multiple regression analysis was performed on the normalized grey matter images with MMI scores as the main regressor. Age, gender and total brain volumes were included as covariates of no interest for all the regressions. To detect voxels in which regional gray matter density was correlated with MMI scores, we adopted a stringent threshold of $p < .05$ with family-wise error whole-brain corrected.

Functional Connectivity Analysis

To perform the functional connectivity analysis, we used the Conn functional connectivity toolbox version 13 (<http://www.nitrc.org/projects/conn>; [21]) combined with preprocessing procedures of SPM8. The preprocessing steps, listed in order, included correction for slice timing, realignment of the time series data to the first volume (i.e. motion correction), co-registration of functional MRI time series to the corresponding structural MRI, segmentation of images into separate tissue types such as grey matter, white matter and cerebrospinal fluid (CSF), and normalization to the standard MNI template and spatial smoothing with a Gaussian filter (FWHM = 8 mm). The time series data were then bandpass filtered to 0.01 Hz–0.1 Hz.

For the seed-based functional connectivity analysis, we used a single significant cluster found in the VBM analysis as the seed region-of-interest (ROI). The mean time series extracted from the ROI was used as a regressor in a multiple regression model at an individual level analysis. To minimize the influences of confounding factors, regressors for the six motion correction parameters from the preprocessing were included. In addition, the mean BOLD signals for the grey matter, white matter and CSF were extracted from the masks created from the segmentation procedure, and were also included as regressors to minimize variances associated with these global signals. Temporal correlations between the ROI signal and the rest of the brain were computed and the correlations with the seed ROI were converted to Z scores using the Fisher transformation for second-level significance analyses.

With the Z-transformed statistical image, we first determined brain regions showing functional connectivity with the seed ROI using a voxel-wise threshold of $p_{FWE-corrected} < 0.05$. Subsequently, we used a less stringent threshold of $p < 0.001$ (uncorrected) as a mask to capture ACC connected regions for a second level analysis in which we aimed to find brain regions with correlated with MMI scores. We included age, gender and total intracranial volumes as covariates and adopted a threshold of $p < 0.05$ with family-wise

error corrected for the volume defined by the initial mask. The rationale for initial masking was to ensure that our analysis was constrained to brain regions showing correlated activity with the seed region. Even if we found a correlation with individual differences outside these regions, such findings would likely reflect spurious correlations. We adopted a less stringent threshold for the masking in order to increase the power of our second level analyses.

Processed imaging data as well as datasets containing the variables for both VBM and functional connectivity regression analyses are made publicly available at: <http://dx.doi.org/10.6084/m9.figshare.1030286>.

Results

VBM analysis revealed a negative association between MMI scores and gray matter density in the anterior cingulate cortex (Figure 1; ACC; $t(70) = 5.16$, $p_{FWE-corrected} < .05$, Cluster size = 158 voxels $\times 1.5^3 = 533 \text{ mm}^3$; peak MNI coordinate: $x = 12$, $y = 41$, $z = 3$). No other brain regions showed significant correlations with MMI scores. Thus, higher media-multitasking was associated with smaller gray matter volumes in the ACC. However, correlational analyses between MMI and BFI scores revealed a highly significant association between Extraversion and MMI scores (Table 2; $r = 0.347$, $p = 0.002$). As such, we suspected that the observed MMI-ACC gray matter association could be confounded by individual differences in extraversion scores. In view of this, we repeated the earlier VBM analysis further controlling for BFI scores as additional covariates. We ran a multiple regression (with gray matter density as dependent variable) including MMI and all Big Five trait scores as predictors along with the demographic covariates. A significant negative relationship was observed between MMI and gray matter volume in the identical ACC region ($t(65) = 5.08$, $p_{FWE-corrected} < .05$, Cluster size = 74 voxels $\times 1.5^3 = 250 \text{ mm}^3$; peak MNI coordinate: $x = 12$, $y = 40$, $z = 3$). This suggested that there is a unique association between MMI and gray matter density in the ACC independent of variations in the Big Five personality traits.

To shed light on the functional significance of our VBM results, we sought to pinpoint, via functional connectivity analyses, brain regions that exhibited significant connectivity with our obtained ACC region-of-interest (ROI). This analysis revealed that activity in the obtained ACC ROI was correlated with multiple brain regions typically characterized as the Default Mode Network including the bilateral temporo-parietal junctions (TPJ; right hemisphere, $x = 48$, $y = -64$, $z = 36$, $p_{FWE-corrected} < 0.05$; left hemisphere, $x = -44$, $y = -70$, $z = 36$) and precuneus ($x = 4$, $y = -68$, $z = 30$, $p_{FWE-corrected} < 0.05$) among other regions (Table 3). These results suggested that the ACC ROI we found with the VBM analysis are likely to fall within the DMN. Next, we further investigated if MMI scores were associated with connectivity between our ACC ROI and DMN regions. Regression analyses were run on z-transformed correlations between ACC and DMN regions with MMI as the main predictor and age, gender and total brain volume as covariates. No significant associations emerged at $p_{FWE-corrected} < 0.05$. However, at a less stringent threshold of $p_{uncorrected} < 0.001$, higher MMI scores was associated with weaker connectivity between the ACC ROI and the precuneus (Figure 2; precuneus; $t(40) = 5.22$, $p_{uncorrected} < 0.001$, Cluster size = 159 mm^3 ; Peak MNI coordinate: $x = 10$, $y = -50$, $z = 18$). We emphasize that our connectivity results were obtained at a less stringent threshold and provided limited evidence for us to make conclusions about MMI and functional

Table 2. Correlations between Media multitasking index scores and Big Five Inventory scores.

Big Five Traits	Pearson's <i>r</i>	<i>p</i>
Extraversion	0.347	0.002
Agreeableness	0.173	0.138
Conscientiousness	0.070	0.552
Neuroticism	−0.131	0.262
Openness	0.100	0.391

doi:10.1371/journal.pone.0106698.t002

connectivity associations. As such, this set of findings served solely in the functional interpretation of our VBM results.

Discussion

As hypothesized, the present study revealed a significant relationship between media multitasking and brain structure

variations: Individuals who reported higher amounts of media multitasking had smaller gray matter density in the ACC. This association was significant at a stringent threshold ($p_{FWE-corrected} < 0.05$) and was independent of the Big Five personality trait differences. We discuss possible interpretations of our structural

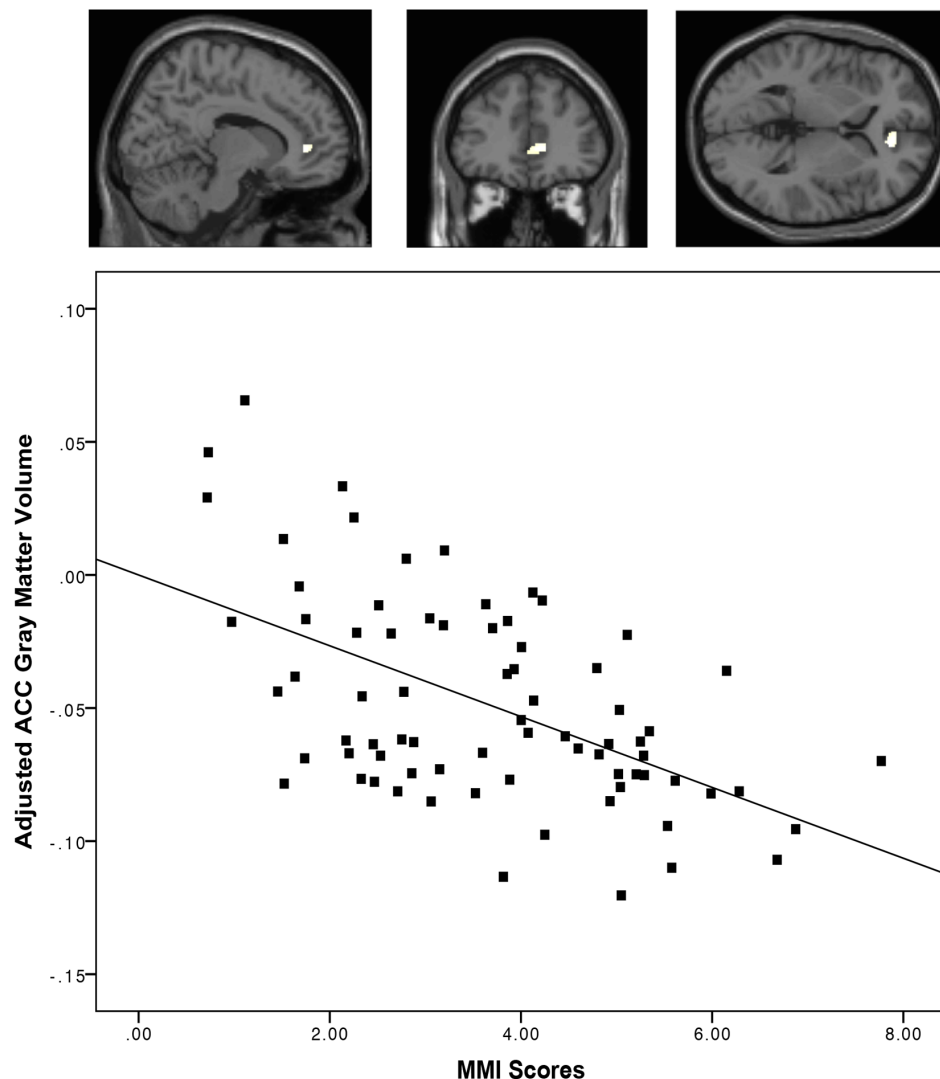


Figure 1. VBM regression analyses revealed that MMI scores were significantly associated with gray matter density in the ACC ($t(70) = 5.16$, $p_{FWE-corrected} < 0.05$, Cluster size = 158 voxels \times $1.5^3 = 533 \text{ mm}^3$; peak MNI coordinate: $x = 12$, $y = 41$, $z = 3$). Adjusted gray matter density in the peak voxel (Y-axis) was negatively correlated ($r = -0.54$, $p < 0.001$) with MMI scores (X-axis). doi:10.1371/journal.pone.0106698.g001

Table 3. Brain regions exhibiting functional connectivity with ACC ROI.

Brain Region	Brodmann's Area	Peak Voxel		Cluster Size (Voxels)
		MNI: <i>x,y,z</i>	<i>t</i>	
R. Mid Cingulate Cortex	23	6, -28, 40	13.68	5011
R. Precuneus	7	4, -68, 39	12.12	
L. Superior Frontal Gyrus	32	-18, 28, 46	11.20	555
R. Temporoparietal Junction	39	48, -64, 36	9.70	755
L. Temporoparietal Junction	39	-44, -70, 36	9.57	609
L. Insula	48	-30, 14, -12	8.28	507

$P_{FWE-corrected} < 0.05$.

doi:10.1371/journal.pone.0106698.t003

correlates in the light of recent evidence about ACC functions and MMI behavioral correlates.

The ACC serves as a crucial nexus of information processing pathways in the brain and has been implicated in sensorimotor, nociceptive, higher cognitive and emotional/motivational processes [22,23]. Of these, we posit that our obtained ACC region is most likely linked with higher cognitive processes since media multitasking has been consistently associated with cognitive control performance [2,10,11,24]. Furthermore, the ACC ROI exhibited significant functional connectivity with the DMN brain regions that were also typically linked with higher cognitive operations [25,26].

In terms of cognitive processing, the ACC is generally thought to be involved in error or conflict detection [27,28]. ACC activations are typically observed in tasks that concurrently activated incompatible responses i.e. the Stroop Task [29,30], selective attention [31] and flanker task [32,33]. Notably, ACC has been implicated in dual-task paradigms [34,35] where an individual is faced with competing stimuli and responses associated with two or more tasks. Analogous to this, in media multitasking,

individuals are confronted with distinct task demands associated with the multiple media types they are using simultaneously. As such, our obtained ROI could be implicated in dual-task related cognitive control functions. One critical caveat is that the abovementioned functions are normally attributed to the dorsal ACC as opposed to the rostral region where our ROI is situated [23,32,35,36]. However, researchers have noted that this delineation is not absolute [23,34,37]. In particular, in support of our present interpretation, Dreher and colleagues [34] reported that the rostral ACC is uniquely involved in conflict detection in the context of dual-tasking.

Our main finding indicated that heavier media multitaskers had smaller ACC volumes. To elucidate possible behavioral implications of reduced ACC volumes in heavy multitaskers, we examined behavioral studies linking MMI and cognitive control. A landmark study by Ophir et al. [2] first revealed the relationship between increased media multitasking activity and poorer cognitive control. They engaged participants in a range of cognitive control tasks such as the Stroop task, task-switching, distractor filtering and the n-back tasks. In the face of distractors, heavy multitaskers (relative

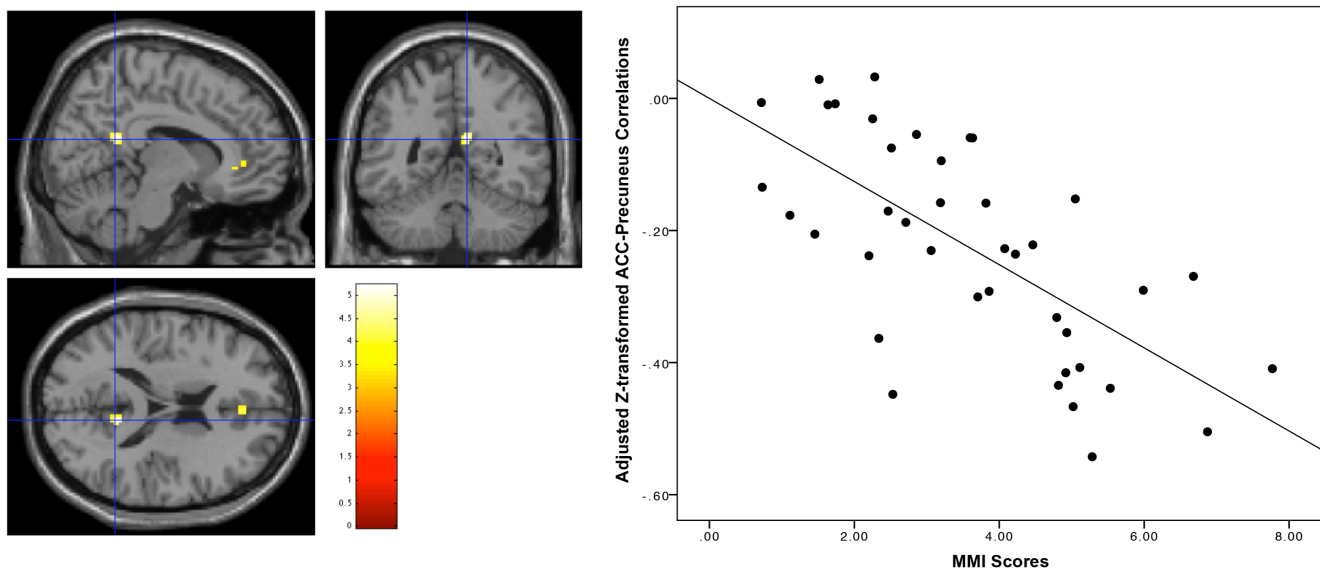


Figure 2. Regression analyses revealed that connectivity between the ACC ROI and the Precuneus (intersection of blue lines) was negatively associated with MMI scores (Precuneus; $t(40) = 5.22$, $P_{FWE-uncorrected} < 0.001$, Cluster size = 159 mm^3 ; Peak MNI coordinate: $x = 10$, $y = -50$, $z = 18$). There was a negative relationship ($r = -0.68$, $p < 0.001$) between adjusted Z-transformed ACC-Precuneus correlations (Y-axis) and MMI scores (X-axis).

doi:10.1371/journal.pone.0106698.g002

to lighter multitaskers) were slower in detecting changes in visual patterns, more susceptible to false recollections of the distractors during a memory task, and were slower in task switching. The authors suggested that heavy multitaskers were less able to volitionally restrain their attention only to task relevant information. Lui and Wong [24] provided further evidence that heavier multitaskers were worse at inhibiting task-irrelevant stimuli and consequently were able to perform better in multisensory integration tasks. A subsequent study [11] showed that heavy multitaskers performed worse on the Operation Span Task (OSPAN) which was highly similar to a dual-task paradigm since participants were required to concurrently solve math problems and memorize presented letters. Heavy multitaskers also reported more failures of attention in everyday life [38]. However, one recent study by Alzahabi and Becker [10] reported contrary findings: heavier multitaskers were not worse at dual-task performance and were better at task-switching. They were also unable to replicate Ophir et al.'s findings despite using identical tasks. The authors noted that their sample was primarily female and this might have resulted in their discrepant findings. They highlighted the importance of longitudinal studies to reveal robust relationships between MMI and cognitive control.

In summary, existing MMI literature generally suggests that individuals who engage in heavier media-multitasking show poorer cognitive control abilities. Our present findings extend this literature by linking heavier media-multitasking activity with smaller volumes in the ACC: a brain region that is implicated in cognitive control based on converging neuroimaging evidence. We emphasize, however, that more work is required to establish the relationship between ACC structure and cognitive control abilities. Studies of patients with ACC lesions have yielded very mixed perspectives about the necessity of ACC in its implicated cognitive functions [39,40,41].

There is also a possibility that our obtained ACC region is involved in emotional/motivational processes since it is situated in the rostral ACC that is typically linked with motivation and emotion processing [23]. Reduced ACC volumes have been often implicated in disorders involving aberrant emotional-motivational processing such as obsessive-compulsive disorder [42], post-traumatic stress disorder [43], depression [44] and drug and non-drug related addictions [45,46]. Based on this perspective, it is plausible that heavier media multitaskers, with reduced ACC volumes, might be less disposed in emotional and motivational regulation. Indeed, higher MMI scores are found to correlate with increased neuroticism, sensation-seeking and impulsivity [3,11]

and negative socio-emotional outcomes [4]. Interestingly, the pattern of brain structural differences obtained in the present study was similar to the neural correlates of Internet addiction (IA). Individuals with IA, defined simply as pathological overuse of the Internet or computers, were found to have decreased gray and white matter densities in the ACC [46,47,48]. There could be a possibility that the two constructs, media multitasking and IA, were overlapping: the MMI provided a measure of how much people used multiple devices at once and this could be related to IA which implicates an excessive use of computers and internet.

An important limitation to the present work is that our results are obtained from a cross-sectional study on the relationship between media multitasking behavior and brain structure. As such, the direction of causality between them cannot be determined. Although it is conceivable that individuals with smaller ACC are more susceptible to multitasking due to weaker ability in cognitive control or socio-emotional regulation, it is equally plausible that higher levels of exposure to multitasking situations lead to structural changes in the ACC. A longitudinal study is required to unambiguously determine the direction of causation. Our current findings open a way to such research by providing an empirical link between media multitasking activity and structural differences in the ACC. One other caveat is that the present findings might not extend beyond our studied population that is relatively highly educated and well exposed to technology. Indeed media consumption patterns could be highly influenced by demographic factors [1]. As such, future studies should examine the role of demographic factors such as education and socio-economic status in moderating the relationship between media multitasking, cognitive performance and brain structures.

In conclusion, individuals who engaged in more media multitasking activity had smaller gray matter volumes in the ACC. This could also possibly explain the poorer cognitive control performance and negative socio-emotional outcomes associated with increased media-multitasking. While the cross-sectional nature of our study does not allow us to specify the direction of causality, our results brought to light novel associations between individual media multitasking behaviors and ACC structure differences.

Author Contributions

Conceived and designed the experiments: KL RK. Performed the experiments: KL RK. Analyzed the data: KL RK. Contributed reagents/materials/analysis tools: KL RK. Wrote the paper: KL RK.

References

1. Rideout VJ, Foehr UG, Roberts DF (2010) Generation M2: Media in the lives of 8- to 18-year-olds. Menlo Park, CA.
2. Ophir E, Nass C, Wagner AD (2009) Cognitive control in media multitaskers. *Proceedings of the National Academy of Sciences of the United States of America* 106: 15583–15587.
3. Becker MW, Alzahabi R, Hopwood CJ (2013) Media multitasking is associated with symptoms of depression and social anxiety. *Cyberpsychology, behavior and social networking* 16: 132–135.
4. Pea R, Nass C, Meheula L, Rance M, Kumar A, et al. (2012) Media use, face-to-face communication, media multitasking, and social well-being among 8- to 12-year-old girls. *Developmental psychology* 48: 327–336.
5. Junco R, Cotton SR (2010) Perceived academic effects of instant messaging use. *Computers and Education* 56: 370–378.
6. Blakemore C, Van Sluyters RC (1975) Innate and environmental factors in the development of the kitten's visual cortex. *The Journal of physiology* 248: 663–716.
7. Draganski B, Gaser C, Busch V, Schuierer G, Bogdahn U, et al. (2004) Neuroplasticity: changes in grey matter induced by training. *Nature* 427: 311–312.
8. Boyke J, Driemeyer J, Gaser C, Buchel C, May A (2008) Training-induced brain structure changes in the elderly. *The Journal of neuroscience: the official journal of the Society for Neuroscience* 28: 7031–7035.
9. Kanai R, Rees G (2011) The structural basis of inter-individual differences in human behaviour and cognition. *Nature reviews Neuroscience* 12: 231–242.
10. Alzahabi R, Becker MW (2013) The association between media multitasking, task-switching, and dual-task performance. *Journal of experimental psychology Human perception and performance* 39: 1485–1495.
11. Sanbonmatsu DM, Strayer DL, Medeiros-Ward N, Watson JM (2013) Who multi-tasks and why? Multi-tasking ability, perceived multi-tasking ability, impulsivity, and sensation seeking. *PLoS one* 8: e54402.
12. Kochlin E, Ody C, Kouneiher F (2003) The architecture of cognitive control in the human prefrontal cortex. *Science* 302: 1181–1185.
13. Marois R, Ivanoff J (2005) Capacity limits of information processing in the brain. *Trends in cognitive sciences* 9: 296–305.
14. Dux PE, Ivanoff J, Asplund CL, Marois R (2006) Isolation of a central bottleneck of information processing with time-resolved fMRI. *Neuron* 52: 1109–1120.
15. Miller EK, Cohen JD (2001) An integrative theory of prefrontal cortex function. *Annual review of neuroscience* 24: 167–202.
16. Burgess PW, Veitch E, de Lacy Costello A, Shallice T (2000) The cognitive and neuroanatomical correlates of multitasking. *Neuropsychologia* 38: 848–863.
17. DeYoung CG, Hirsh JB, Shane MS, Papademetris X, Rajeevan N, et al. (2010) Testing predictions from personality neuroscience. Brain structure and the big five. *Psychological science* 21: 820–828.

18. Ashburner J (2007) A fast diffeomorphic image registration algorithm. *NeuroImage* 38: 95–113.
19. John OP, Srivastava S (1999) The Big Five trait taxonomy: History, measurement, and theoretical perspectives. In: Pervin LA, John OP, editors. *Handbook of personality: Theory and research*. New York: Guilford Press. 102–138.
20. Ashburner J, Friston KJ (2000) Voxel-based morphometry—the methods. *NeuroImage* 11: 805–821.
21. Whitfield-Gabrieli S, Moran JM, Nieto-Castanon A, Triantafyllou C, Saxe R, et al. (2011) Associations and dissociations between default and self-reference networks in the human brain. *NeuroImage* 55: 225–232.
22. Devinsky O, Morrell MJ, Vogt BA (1995) Contributions of anterior cingulate cortex to behaviour. *Brain: a journal of neurology* 118 (Pt 1): 279–306.
23. Bush G, Luu P, Posner MI (2000) Cognitive and emotional influences in anterior cingulate cortex. *Trends in cognitive sciences* 4: 215–222.
24. Lui KF, Wong AC (2012) Does media multitasking always hurt? A positive correlation between multitasking and multisensory integration. *Psychonomic bulletin & review* 19: 647–653.
25. Raichle ME, MacLeod AM, Snyder AZ, Powers WJ, Gusnard DA, et al. (2001) A default mode of brain function. *Proceedings of the National Academy of Sciences of the United States of America* 98: 676–682.
26. Buckner RL, Andrews-Hanna JR, Schacter DL (2008) The brain's default network: anatomy, function, and relevance to disease. *Annals of the New York Academy of Sciences* 1124: 1–38.
27. Carter CS, Macdonald AM, Botvinick M, Ross LL, Stenger VA, et al. (2000) Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Sciences of the United States of America* 97: 1944–1948.
28. Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD (2001) Conflict monitoring and cognitive control. *Psychological review* 108: 624–652.
29. Bush G, Whalen PJ, Rosen BR, Jenike MA, McInerney SC, et al. (1998) The counting Stroop: an interference task specialized for functional neuroimaging—validation study with functional MRI. *Human brain mapping* 6: 270–282.
30. Leung HC, Skudlarski P, Gatenby JC, Peterson BS, Gore JC (2000) An event-related functional MRI study of the stroop color word interference task. *Cerebral cortex* 10: 552–560.
31. Corbetta M, Miezin FM, Dobmeyer S, Shulman GL, Petersen SE (1991) Selective and divided attention during visual discriminations of shape, color, and speed: functional anatomy by positron emission tomography. *The Journal of neuroscience: the official journal of the Society for Neuroscience* 11: 2383–2402.
32. Botvinick M, Nystrom LE, Fissell K, Carter CS, Cohen JD (1999) Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature* 402: 179–181.
33. Casey BJ, Thomas KM, Welsh TF, Badgaiyan RD, Eccard CH, et al. (2000) Dissociation of response conflict, attentional selection, and expectancy with functional magnetic resonance imaging. *Proceedings of the National Academy of Sciences of the United States of America* 97: 8728–8733.
34. Dreher JC, Grafman J (2003) Dissociating the roles of the rostral anterior cingulate and the lateral prefrontal cortices in performing two tasks simultaneously or successively. *Cerebral cortex* 13: 329–339.
35. Erickson KI, Colcombe SJ, Wadhwani R, Bherer L, Peterson MS, et al. (2005) Neural correlates of dual-task performance after minimizing task-preparation. *NeuroImage* 28: 967–979.
36. Milham MP, Banich MT, Webb A, Barad V, Cohen NJ, et al. (2001) The relative involvement of anterior cingulate and prefrontal cortex in attentional control depends on nature of conflict. *Brain research Cognitive brain research* 12: 467–473.
37. Kiehl KA, Liddle PF, Hopfinger JB (2000) Error processing and the rostral anterior cingulate: an event-related fMRI study. *Psychophysiology* 37: 216–223.
38. Ralph BC, Thomson DR, Cheyne JA, Smilek D (2013) Media multitasking and failures of attention in everyday life. *Psychological research*.
39. Fellows LK, Farah MJ (2005) Is anterior cingulate cortex necessary for cognitive control? *Brain: a journal of neurology* 128: 788–796.
40. Swick D, Turken AU (2002) Dissociation between conflict detection and error monitoring in the human anterior cingulate cortex. *Proceedings of the National Academy of Sciences of the United States of America* 99: 16354–16359.
41. Swick D, Jovanovic J (2002) Anterior cingulate cortex and the Stroop task: neuropsychological evidence for topographic specificity. *Neuropsychologia* 40: 1240–1253.
42. Rotge JY, Guehl D, Dilharreguy B, Tignol J, Bioulac B, et al. (2009) Meta-analysis of brain volume changes in obsessive-compulsive disorder. *Biological psychiatry* 65: 75–83.
43. Yamasue H, Kasai K, Iwanami A, Ohtani T, Yamada H, et al. (2003) Voxel-based analysis of MRI reveals anterior cingulate gray-matter volume reduction in posttraumatic stress disorder due to terrorism. *Proceedings of the National Academy of Sciences of the United States of America* 100: 9039–9043.
44. Caetano SC, Kaur S, Brambilla P, Nicoletti M, Hatch JP, et al. (2006) Smaller cingulate volumes in unipolar depressed patients. *Biological psychiatry* 59: 702–706.
45. Franklin TR, Acton PD, Maldjian JA, Gray JD, Croft JR, et al. (2002) Decreased gray matter concentration in the insular, orbitofrontal, cingulate, and temporal cortices of cocaine patients. *Biological psychiatry* 51: 134–142.
46. Zhou Y, Lin FC, Du YS, Qin LD, Zhao ZM, et al. (2011) Gray matter abnormalities in Internet addiction: a voxel-based morphometry study. *European journal of radiology* 79: 92–95.
47. Yuan K, Qin W, Wang G, Zeng F, Zhao L, et al. (2011) Microstructure abnormalities in adolescents with internet addiction disorder. *PloS one* 6: e20708.
48. Lin F, Zhou Y, Du Y, Qin L, Zhao Z, et al. (2012) Abnormal white matter integrity in adolescents with internet addiction disorder: a tract-based spatial statistics study. *PloS one* 7: e30253.